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Code 2A

(NASA TM X-51005)

MECHANICAL PROPERTIES OF COMPOSITE MATERIALS

FOR EXPANDABLE SPACE STRUCTURES

By Howard L. Price [1963] 21p

NASA, Langley Research Center,
Langley Station, ~~Hampton~~, Va.

Presented at the Conf. on Aerospace Expandable Structures,

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~~NASA Centers Only.~~

Dayton, Ohio,
Oct. 22-24, 1963

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ABSTRACT

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An analysis is presented of tests to determine the mechanical properties of several composite materials which are used or have potential use in aerospace structures. The composites are approximately 0.001 inch thick, and are laminates of aluminum foil and Mylar film, aluminum foil and polypropylene film, and vapor-deposited aluminum on Mylar film. The analysis is made on the basis of tensile stress-strain, stress-relaxation, and flexural-stiffness tests. The stress-strain and stress-relaxation tests illustrate the mechanical behavior of the composites as influenced by their composition. A comparison is made of the flexural rigidity of the composites as measured by the heavy elastica method.

AUTHOR

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INTRODUCTION

Some of the mechanical and structural applications of materials, on Earth as well as in space, are such that no single material will adequately meet the requirements. As a result, composite materials are often necessary and sometimes offer advantages which are not found in single materials. A composite material is a combination of materials which seeks to utilize certain outstanding properties of each. It has been said (ref. 1) that "the strongest and most efficient materials created by nature . . . and by man . . . have always been composite materials." It is obvious that both strength and efficiency are highly desirable in aerospace structures. Therefore, composite materials can be used to advantage in such structures.

Composite structural materials can be classified into at least three groups. One group is the bonded-layer type of composite, such as laminates. A second group is the matrix type, such as reinforced plastics, and the third group is the atomic structure type which includes the organometallic polymers. This paper will deal with the mechanical properties of some bonded-layer composites, in particular, some aluminum-plastic laminates and an aluminized plastic film. The composites are used or have potential use in aerospace structures, such as passive communications satellites (ref. 2), air-density-measurement satellites (ref. 3), and solar energy concentrators (ref. 4). The mechanical properties were determined by means of tensile tests and stress-relaxation tests, and the flexural rigidity of the composites is measured by the heavy elastica method.

DESCRIPTION OF MATERIALS

The materials are described in table 1 which lists both the nominal thickness and the thickness as measured by an electrically driven micrometer. The measured thickness was used to calculate the cross-section area of the test specimens. Figure 1 shows the cross sections of the composites drawn to approximately the same scale. It is possible, then, to obtain some idea of the relative thicknesses of the materials and their components. The nominal thicknesses are indicated in figure 1.

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The Echo I material is the type which was used to fabricate the Echo I passive communications satellite. The vapor-deposited aluminum serves as a reflecting surface for radio and radar waves and reduces the degradation by ultraviolet radiation of the Mylar film in the space environment (ref. 5). The Echo (A-12) laminate is the type used to fabricate a 135-foot-diameter sphere. Although it can also be used for communications experiments, the Echo (A-12) balloon was originally designed to demonstrate the feasibility of mechanically rigidizing a large structure in space (ref. 2). The Explorer IX laminate was used to fabricate a 12-foot-diameter air-density-measurement satellite (ref. 3). The Explorer IX satellite has been in orbit since February 1961 and has provided valuable data on the density of the upper atmosphere. Although the aluminum-Mylar (A/M) laminate and the aluminum-Mylar-aluminum (A/M/A) laminate have not been used in space structures it will be shown later that each laminate has certain properties which could be highly useful.

The X-32B laminate was designed to allow a large part of the incident solar radiation to pass through but at the same time to reflect radar waves (ref. 6). Although the solar pressure is quite small (1.3×10^{-9} psi, ref. 7), it can have a considerable effect on large, lightweight, balloon-like structures. For example, solar pressure has helped to alter the orbit of Echo I since the satellite was launched in August 1960 (ref. 8). However, the exposed polypropylene in the X-32B laminate will transmit the solar radiation and the effect of solar pressure on a satellite would be reduced. The etched areas in the aluminum foil are sufficiently small so that the laminate behaves as a solid reflector to radar with a wavelength of at least 3.53 cm.

DESCRIPTION OF TESTS

Three types of tests were used to determine the mechanical behavior of the composite materials - the stress-strain test at constant strain rate, the stress-relaxation test, and the flexural stiffness test.

The stress-strain tests were performed on an Instron Model TT-C testing machine on which the cross-head moves at a constant rate so that the strain rate was constant. The strain was determined by dividing the change in the specimen length by the original distance between the testing machine grips, which was 5 inches. The values of elongation refer to the strain of the test specimen when the specimen failed. The load was measured by a 50-pound capacity load cell, and the area of the test specimen was taken as the product of the width and the total measured thickness of the specimen without regard to the relative areas of metal foil and plastic film.

The stress-relaxation tests also were performed on an Instron testing machine. The test specimen was elongated at a strain rate of 0.04 inch per inch per minute to some predetermined stress. The testing machine cross-head was stopped and observations were made of the continuous relaxation of the stress at the fixed strain for a period of 1,000 minutes (16 hours and 40 minutes).

The flexural rigidity of the composites was measured by the heavy elastica method. The rigidity of the composites is especially important when they are used in large, balloon-like structures which have no load-carrying framework to support the envelope or skin. Satellites in orbit about the Earth are subject to small but continuous deforming loads, such as solar pressure or atmospheric drag (ref. 7). These deforming loads can contribute to the bending or buckling of large areas of unsupported skin. The Echo I, for example, has undergone considerable deformation (ref. 9). The diameter may have decreased (from the original 100 feet) and what appear to be large flat areas have developed in the skin.

The derivation of the equations for use in the flexural stiffness test may be found in references 10 and 11. A test procedure for measuring the stiffness of fabrics is given in reference 12. In order to measure the rigidity of the composites it was necessary to use a modified test procedure which is presented in reference 13. The present tests were performed by projecting a strip of material from a horizontal surface (fig. 2(a)). Measurements were made of the length of the overhang l and the deflection θ of the free end below the horizontal. By entering the curve in figure 2(b) with the measured value of θ, the ratio c/l can be determined, where c is referred to as bending length. The flexural rigidity, then, is simply the product of c^3 and the weight of the strip per unit length.

RESULTS AND DISCUSSION

The tensile properties and flexural rigidity of the composites are listed in tables 2 and 3 and illustrated in figures 3 to 6. These data were obtained from references 13 and 14 for 1/2-inch-wide strips of material and have been normalized to unit width.

Tensile Properties

The tensile properties of the composites are listed in table 2 which includes the values of the tensile strength, Young's modulus, and elongation at break. The Echo I material has the highest tensile strength (27,000 psi) and the A/M laminate has the lowest (11,600 psi). This low value is the result of the comparatively early failure of the aluminum foil when the laminate is being elongated. When the aluminum foil breaks, the laminate is considered to have failed even though the plastic film may be intact. In the case of homogeneous (that is noncomposite) materials the tensile strength is a valid indication of the load that the material can carry. In comparing composite materials, however, the tensile strength may not be indicative of the load-carrying ability, especially when the total thickness is used to compute the cross-section area. Therefore, table 2 includes the values of the load which is required to break a 1-inch-wide strip of material. The A/M/A laminate has the highest breaking load (61.9 pounds) and the A/M laminate has the lowest (6.4 pounds) of the composites which were tested. The ranking of the six composites according to tensile strength and according to breaking load results in a different sequence, with only the A/M laminate and the X-32B laminate retaining their same position in each sequence.

Table 2 includes the values of Young's modulus which were determined on the basis of total cross-section area. The Young's modulus of the Explorer IX laminate (3.68×10^6 psi) is approximately seven times that of the Echo I material (0.66×10^6 psi). Of more practical interest, however, is the extensional stiffness. The extensional stiffness can be thought of either as the product of Young's modulus and the material thickness, or as the force required to extend a unit width strip of material to twice its original length (i.e., 100-percent strain). The extensional stiffness of the composites is included in table 2. The Echo I material, the A/M laminate, and the X-32B laminate all have an extensional stiffness of nearly 3 pounds per inch. The Explorer IX laminate has the highest value (82.8 pounds per inch) of extensional stiffness of the composites.

Although the extensional stiffness is given in pounds per inch, it does not follow that extending the material to 100-percent strain will result in the force shown in the extensional stiffness column. The reason, of course, is that the composite may yield or even break at much smaller values of strain. However, the extensional stiffness provides a reliable means of evaluating the force required to strain composites of widely different composition.

The elongation at break requires no change for composite materials because the cross-section area does not enter into the calculation as it does for the tensile strength and Young's modulus. Both the Echo I material and the A/M/A laminate have high elongations, on the order of 150 percent. For a test specimen with an original length between the grips of 5 inches, the length at break was about 12.5 inches. The high elongation reflects the large amount of Mylar film which the composites contain. The elongation of the A/M, the Echo (A-12), and the Explorer IX laminates are the strains at which the aluminum foil fails. In general, the Mylar film remains intact.

It is concluded, then, that the A/M/A laminate can withstand the largest tensile load, the Explorer IX laminate has the highest extensional stiffness, and the Echo I material has the highest elongation of the materials which were tested. Furthermore, it can be very misleading to describe the tensile properties of composites by means of the usual tensile strength and Young's modulus values based on total cross-section area. It is more accurate, especially when comparing different composite materials, to present the tensile properties in terms of breaking load, extensional stiffness, and elongation.

Calculated Stress-Strain Values

When a composite material is stressed, the components are not, in general, under the same stress. It is instructive to determine what stresses the components experience so that, if the properties of the components are known, a composite can be constructed which will have certain predetermined properties. Therefore, the stress at selected strains was calculated for the Echo (A-12) laminate and the results are shown in figure 3.

The experimentally determined stress-strain curves are shown in figure 3 for the aluminum foil and Mylar film which is used in the Echo (A-12) laminate. The curves were obtained from tests of 1/2-inch-wide strips of material which were loaded at a strain rate of 0.04 inch per inch per minute. In calculating the stress on the composite it is assumed that the composite load is the sum of the loads on the components (ref. 15). In addition, it is assumed that the aluminum and the Mylar film undergo equal strain in the laminate so there is no slippage between the layers. For a given value of strain the load on each component is determined from the stress-strain curve. The component loads are added and their sum is divided by the area of the laminate, thereby providing the calculated laminate stress for the given strain.

The calculated stress-strain values are compared with the experimental stress-strain curve for the Echo (A-12) laminate in figure 3. There is fairly good agreement for strains up to about 0.5 percent which is beyond the yield stress of the laminate. At higher strains the calculations indicate a lower stress than those that were actually measured. However, the difference is rather small (about 600 to 700 psi) and fairly constant, suggesting that the Young's modulus for the Mylar film might be higher (0.79×10^6 psi) than the value of 0.69×10^6 psi which was used in the calculations. It is concluded, then, that it is valid to combine the stress-strain curves of the components in order to obtain the stress-strain curve of the laminate.

A comparison of the experimental curves (fig. 3) of the components and the Echo (A-12) laminate shows that, for strains up to about 1.5 percent, the aluminum-foil stress is higher and the Mylar film stress is lower than the laminate stress. At higher strains, or laminate stress above approximately 10,000 psi, the Mylar is more highly stressed than the laminate. Furthermore, a laminate stress of 4,000 to 5,000 psi is required to yield the aluminum foil. Once the aluminum foil has passed its yield stress it will take a permanent set, although the Mylar film will still be elastic. When the laminate is released, the Mylar film will attempt to recover its original, undeformed length. Complete recovery will be prevented by the permanent deformation of the aluminum foil. Therefore, the aluminum will be in compression and the Mylar film will be in tension after the laminate stress is released.

The tension and compression in the components has no apparent effect on the Echo (A-12) laminate. It can be seen from the cross section of the laminate (fig. 1) that the tension force in the Mylar film is balanced by the compression forces in the aluminum on each side of the film. However, in the Echo I material, the A/M laminate, and the Explorer IX laminate the forces are not balanced and the resulting torques deform the material.

In order to illustrate the effect of the torques, 1/2-inch-wide strips of the composites were subjected to several tensile loads and the resulting deformation is shown in figure 4. As the load increases so does the curvature of the composites. The small sections which were cut from the test strips tended to curl into small cylinders. The edges of the test strip of the Echo I material curled after 4 pounds of load so the strip itself did not deform. After 5 pounds of load the vapor-deposited aluminum was so thin that there was no appreciable deformation as shown by the section that was cut from the test strip. Although the torques are small (an estimated 2.5×10^{-4} inch-pound for the A/M laminate subjected to a $1\frac{1}{2}$- pound load) they may become significant in a null gravity field and cause undesirable deformations. On the other hand, such torques might prove to be useful as a restraining or restoring force in a simple spring or damping system.

Stress Relaxation

The effect of loading a laminate until the aluminum has exceeded its yield stress has been demonstrated above and in figure 4. In the case of a laminate with balanced forces, the yielding of the aluminum is indicated by a decrease in the slope of the stress-strain curve (fig. 3). A further indication of the effect is obtained by means of the tensile stress-relaxation test.

The representative stress-relaxation curves for the Echo (A-12) laminate are shown in figure 5 where the stress is plotted against the logarithm of the time in minutes. The tests were conducted with initial laminate stresses in a lower range of 1,000 to 5,000 psi, and with stress in a higher range of 6,000 to 10,000 psi (see ref. 14). At all stress levels the stress decreases approximately linearly with the logarithm of time from 0.1 minute to 1,000 minutes (16 hours and 40 minutes). If the curves are extended they intersect at two points. The curves for the initial stress in the lower stress range intersect at a stress of about 100 psi and a logarithm of time of 17.7. The curves for the higher range stresses intersect at a stress of 1,300 psi and a logarithm of time of 14.8.

The two points of intersection reflect the dual response of the laminate to long time, fixed deformation. For laminate stresses up to 4,000 psi the aluminum foil is still below its yield stress and the Mylar film is at a comparatively low stress of less than 1,500 psi. The aluminum, then, carries most of the load on the laminate so the curves in the lower stress range are virtually those of the aluminum. At the higher stresses the aluminum has exceeded its yield stress and the Mylar film may be loaded to a stress as high as 10,000 psi. Therefore, the laminate undergoes a more rapid rate of stress reduction in the upper stress range than it does in the lower. The difference, however, is rather small. In the lower range the stress decays at the rate of about 4.8 percent of the original stress per decade of time and in the upper range the rate is 6 percent. As a result, if the laminate is fabricated into a structure in such a way that stress gradients occur across the surface of the laminate (gradients caused by such elements as seams, pole caps, or local reinforcements) it is unlikely that the stress gradient will decrease to any practical degree. For example, for an original laminate stress of 10,000 psi, more than 100 years would be required for the laminate to relax to 5,000 psi (fig. 5). It can, of course, be very misleading to extrapolate time-dependent data. The above example, however, although it involves such extrapolation, does give some idea of the long times which would be required for the Echo (A-12) laminate to undergo extensive stress relaxation.

Flexural Rigidity

The flexural rigidity of the composites is listed in table 3 and illustrated in figure 6. The flexural rigidity is the product of Young's modulus, E, and I, the moment of inertia for flexure. Because of its tendency to curl it was impossible to measure the flexural rigidity of the A/M laminate in the same manner as the other composites was measured. Therefore, the flexural rigidity of the laminate was calculated.

All of the flexural rigidity values are quite low for structural purposes. They fall in the range of 10^{-6} to 10^{-4} lb-in.^{2} which is small in comparison to the flexural rigidity of approximately 8×10^{-1} lb-in.^{2} for 0.01-inch-thick aluminum. The lowest value of rigidity, 5.06×10^{6} lb-in.^{2}, is that of the Echo I material. The A/M/A laminate has the highest rigidity, 5.02×10^{-3} lb-in.^{2}. The rigidities relative to the Echo I material are listed in table 3. The Echo (A-12) laminate, which was designed to be stiffer than the Echo I material, is over 100 times as rigid. The ratio of the rigidity of the Echo I material to the Echo (A-12) laminate to the X-32B laminate is 1/115/48. The ratio given in reference 6 for the same composites is approximately 1/57/5. The latter ratio, based on design calculations, is more conservative than the ratio which was determined by the flexural rigidity tests. The difference between the two ratios gives some indication of how difficult it is to obtain agreement between the calculated and the measured flexural rigidities for thin composite materials.

Increased resistance to bending may or may not be an advantage, depending on the application of the composite. If the increased rigidity is accompanied by a substantial weight increase, then the more rigid composite may not be as efficient as one which is less rigid. The flexural rigidity of the composite, divided by its weight per unit area, is taken as the weight efficiency. The values are listed in table 3 and are equal to c^3, the value of c being determined from the curve in figure 2b. In reference 10 the value c is referred to as the bending length and is considered to be a measure of the quality of a fabric. As it is used here c is a measure of the efficiency of a composite material in resisting flexure.

A higher rigidity may be obtained by increasing the thickness of the material. In a homogeneous material the flexural rigidity increases as the cube of the thickness. A thicker material, however, requires a larger volume for packaging and may present some folding problems. Therefore, the flexural rigidity of the composite, divided by its measured thickness, is taken as the thickness efficiency and the values are listed in table 3.

The A/M laminate has the lowest $\left(1.8 \times 10^{-1} \text{ in.}^4\right)$ and the A/M/A laminate has the highest $\left(2.84 \times 10 \text{ in.}^4\right)$ weight efficiency of the composites which were tested. The flexural rigidity of the A/M laminate may be lower than the true value because the rigidity was calculated on the assumption that only the aluminum is effective in bending. Even if the calculated rigidity were in error by as much as 20 percent, the weight efficiency would be comparable to the efficiency of the Echo I material. From the standpoint of thickness, the A/M laminate has a low efficiency of 4.02×10^4 lb-in. The Echo (A-12) laminate has a high thickness efficiency of 1.14×10^6 lb-in.

A comparison of the flexural rigidity, the weight, and the thickness of the composites relative to the Echo I material is shown in figure 6. A logarithmic scale is used for the relative flexural rigidities in order to accommodate the wide spread in the values. Included in figure 6 is a set of curves which show the flexural rigidity which would be equal to a weight or thickness efficiency of 1, 10, 100, and 1,000 times the efficiency of the Echo I material. For example, a composite that is 50 times as rigid but which weighs five times as much would be located on the 10X curve because it would have ten times the weight efficiency of Echo I.

It can be seen in figure 6a that the weight efficiency of the A/M laminate is lower than that of the Echo I material. The highest (135X) efficiency is achieved by the A/M/A laminate followed closely by the Explorer IX laminate which has a weight efficiency that is 133 times that of the Echo I material. The high efficiencies are obtained at a considerable increase in weight of 7 to 8 times the weight of the Echo I material. However, the laminates should prove to be useful in cases in which a small (and, therefore, low total weight) but highly rigid structure is required. The requirements of size and rigidity were in fact encountered in the Explorer IX air-density-measurement satellite (ref. 3). The Explorer IX laminate, then, represents a case in which a laminate was designed for a particular application and then satisfactorily employed for it.

Both the Echo (A-12) laminate and the X-32B laminate have higher weight efficiencies (49 and 30 times) than the Echo I material. The X-32B may be more efficient in orbit than is indicated by figure 6. The reason is that in the flexural rigidity test the gravitational force or weight of the material is the deforming load. The chemical milling of the X-32B laminate removes 58 percent of the aluminum, and relieves the laminate of approximately one-half of the deforming load of solar pressure. The polypropylene windows contribute to the weight which deforms the material in the flexural rigidity test. These same windows would contribute a negligible load under the action of solar pressure. Therefore, the X-32B laminate may be more efficient than the flexural rigidity test indicates.

The thickness efficiencies of the composites are illustrated in figure 6b where it is shown that A/M laminate has the lowest efficiency. The A/M/A, X-32B, and Explorer IX laminates have thickness efficiencies which are approximately 2, 3, and 6 times that of the Echo I material. The Echo (A-12) laminate has the highest efficiency (17 times) and the lowest thickness (2 times) relative to Echo I material. The combination of low thickness and high efficiency indicates that the Echo (A-12) is suitable for large structures, such as the Echo (A-12) satellite, or for large structures in which rigidity is required but packaging space is limited.

The above discussion indicates increased efficiency in resisting bending is accompanied by an increase of weight and/or thickness of the composite. An increase in weight or thickness does not necessarily bring about an increase in efficiency, however. The A/M laminate is an example. It is not good enough, then, to design or use laminates which are heavier or thicker than Echo I material, even though they may have a higher flexural rigidity. The candidate laminate might be no more efficient than a scaled-up version of the Echo I material. On the other hand, an Echo I type material of the thickness of the Explorer IX laminate might present some problems in folding and packaging. As a result, a laminate incorporating aluminum foil might be necessary so that the required flexibility could be achieved, even at the loss of some of the efficiency. A composite material for use in balloon-like structures, then, represents a compromise among the factors of weight, thickness, rigidity, and flexibility.

CONCLUDING REMARKS

The mechanical properties have been determined of six composite materials which have been used or have potential use in aerospace structures.

It has been found that, in comparing the tensile properties of composite materials, it is more accurate to express the properties in terms of breaking load and extensional stiffness rather than strength and Young's modulus. The stress-strain or load-strain curve of a composite can be estimated if the stress-strain curves of the components are known. In the aluminum-Mylar laminates the residual stresses in the components may act in opposite directions. As a result, these forces can severely deform a laminate in which the forces are not balanced. The dual response to long time, fixed strain of a two component laminate has been demonstrated by the stress-relaxation test. For laminate stresses below those at which the aluminum has reached yield, the rate of stress decay is lower than the case in which the aluminum has yielded.

The flexural rigidity of the composites has been measured by the heavy elastica method. It has been found that increased rigidity is obtained at the cost of increased weight and/or thickness.

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TABLE 1.- DESCRIPTION OF COMPOSITE MATERIALS

Material	Nominal thickness, in.	Measured thickness, in.	Weight, lb/in.^{2}	Composition
Echo I	0.0005	0.00042	2.45×10^{-5}	0.5-mil Mylar film with 2,200 Å vapor-deposited aluminum on one side similar to Echo I balloon skin.
A/M Laminate	0.00055	0.00055	3.71×10^{-5}	Two-ply laminate of 0.2-mil aluminum foil and 0.35-mil Mylar film cemented with polyester adhesive.
Echo (A-12)	0.00071	0.0008	5.70×10^{-5}	Three-ply laminate, 0.35-mil Mylar film between 0.2-mil aluminum foil, cemented with polyester adhesive.
A/M/A Laminate	0.00270	0.00285	17.7×10^{-5}	Three-ply laminate, 2-mil Mylar film between 0.35-mil aluminum foil, cemented with polyester adhesive.
Explorer IX	0.002	0.00225	16.4×10^{-5}	Four-ply laminate of 0.5-mil Mylar film and 0.5-mil aluminum foil cemented with polyester adhesive.
X-32B	0.0010	0.0011	3.82×10^{-5}	Three-ply laminate, 0.6-mil polypropylene film between 0.2-mil aluminum foil, cemented with polyester adhesive, 58 percent of aluminum removed in hexagonal pattern by chemical milling.

TABLE 2.- TENSILE PROPERTIES OF 1-INCH-WIDE STRIPS

OF COMPOSITE MATERIALS

Material	Tensile strength, psi	Breaking load, lb	Young's modulus, psi	Extensional stiffness, lb/in.	Elongation
Echo I	27,000	11.3	0.66×10^6	2.77×10^2	158
A/M Laminate	11,600	6.4	0.53×10^6	2.92×10^2	11
Echo (A-12)	13,700	11.0	2.73×10^6	21.84×10^2	12
A/M/A Laminate	21,700	61.9	2.08×10^6	59.28×10^2	149
Explorer IX	13,000	29.3	3.68×10^6	82.80×10^2	26
X-32B	------	14.7	----------	2.85×10^2	43

TABLE 3.- FLEXURAL RIGIDITY OF 1-INCH-WIDE STRIPS OF COMPOSITE MATERIALS AS MEASURED BY THE HEAVY ELASTICA METHOD

Material	Flexural rigidity (EI), lb-in.^{2}	Rigidity relative to Echo I	Weight efficiency, in.^{4}	Thickness efficiency, lb-in.	Remarks
Echo I	5.06×10^{-6}	1	2.1×10^{-1}	6.8×10^{4}	Aluminized side in tension
A/M Laminate	6.67×10^{-6}	1.3	1.8×10^{-1}	4.02×10^{4}	Rigidity calculated assuming aluminum foil effective in bending
Echo (A-12)	5.84×10^{-4}	115	1.03×10	1.14×10^{6}	
A/M/A Laminate	5.02×10^{-3}	992	2.84×10	1.76×10^{5}	
Explorer IX	4.56×10^{-3}	901	2.8×10	4.0×10^{5}	Aluminum side in tension
X-32B	2.42×10^{-4}	48	6.3	1.82×10^{5}	

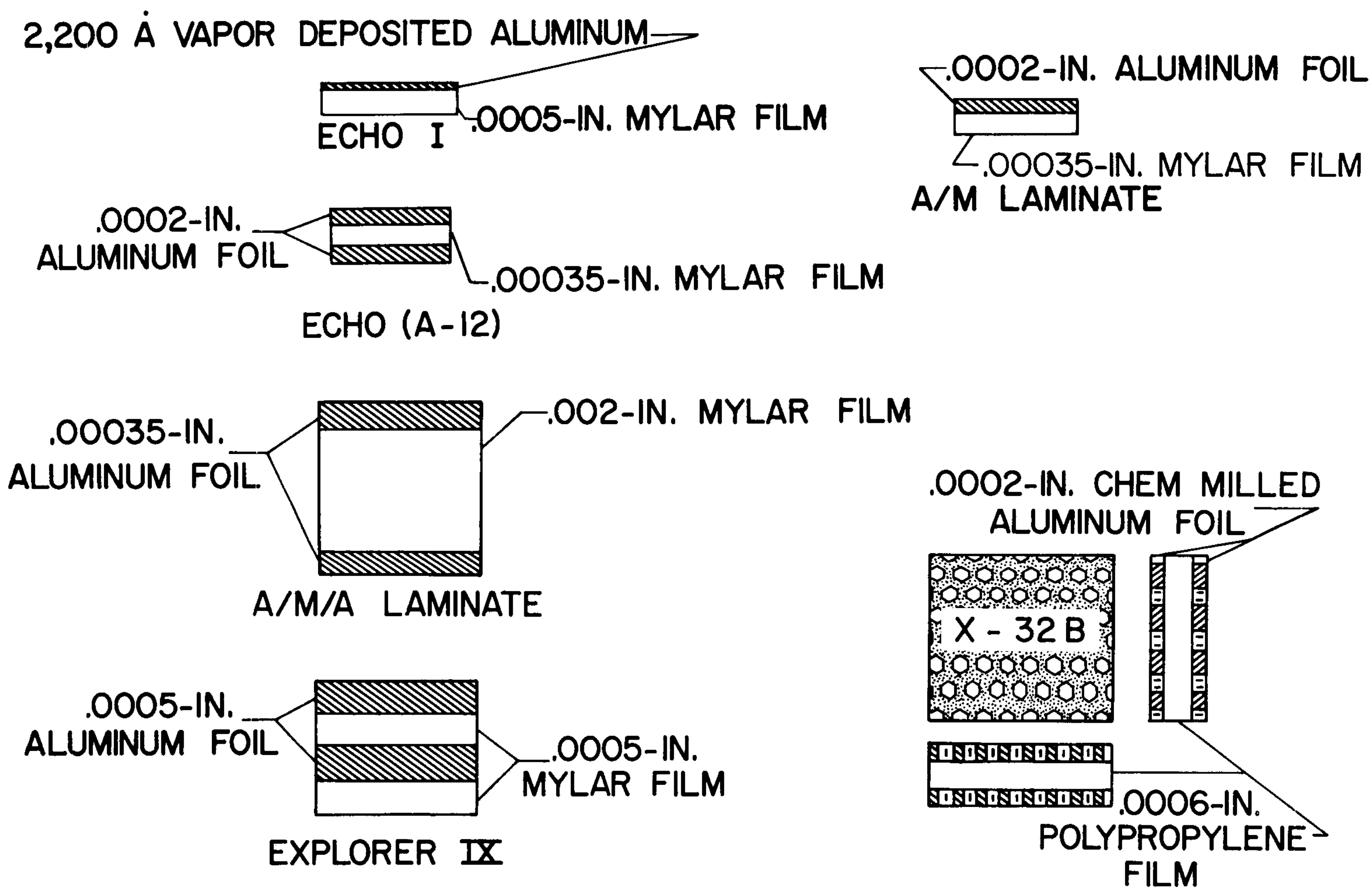

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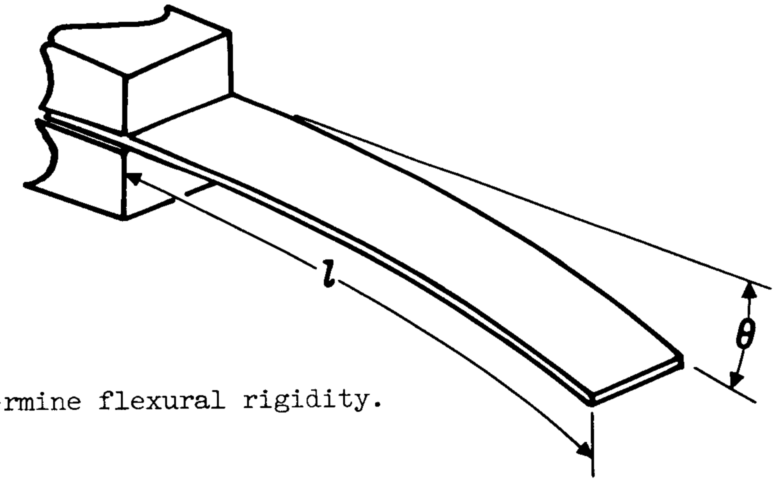
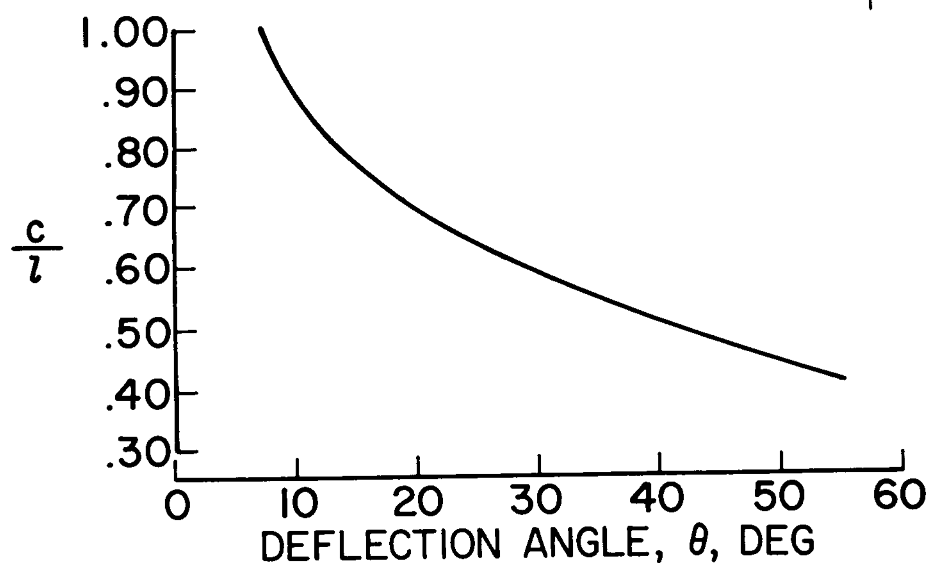
Figure 1.- Cross section of composite materials.



(a) Measurements required to determine flexural rigidity.



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(b) Relationship between deflection angle θ, length of overhang l, and bending length c.

Figure 2.- The heavy elastica method of measuring flexural rigidity.

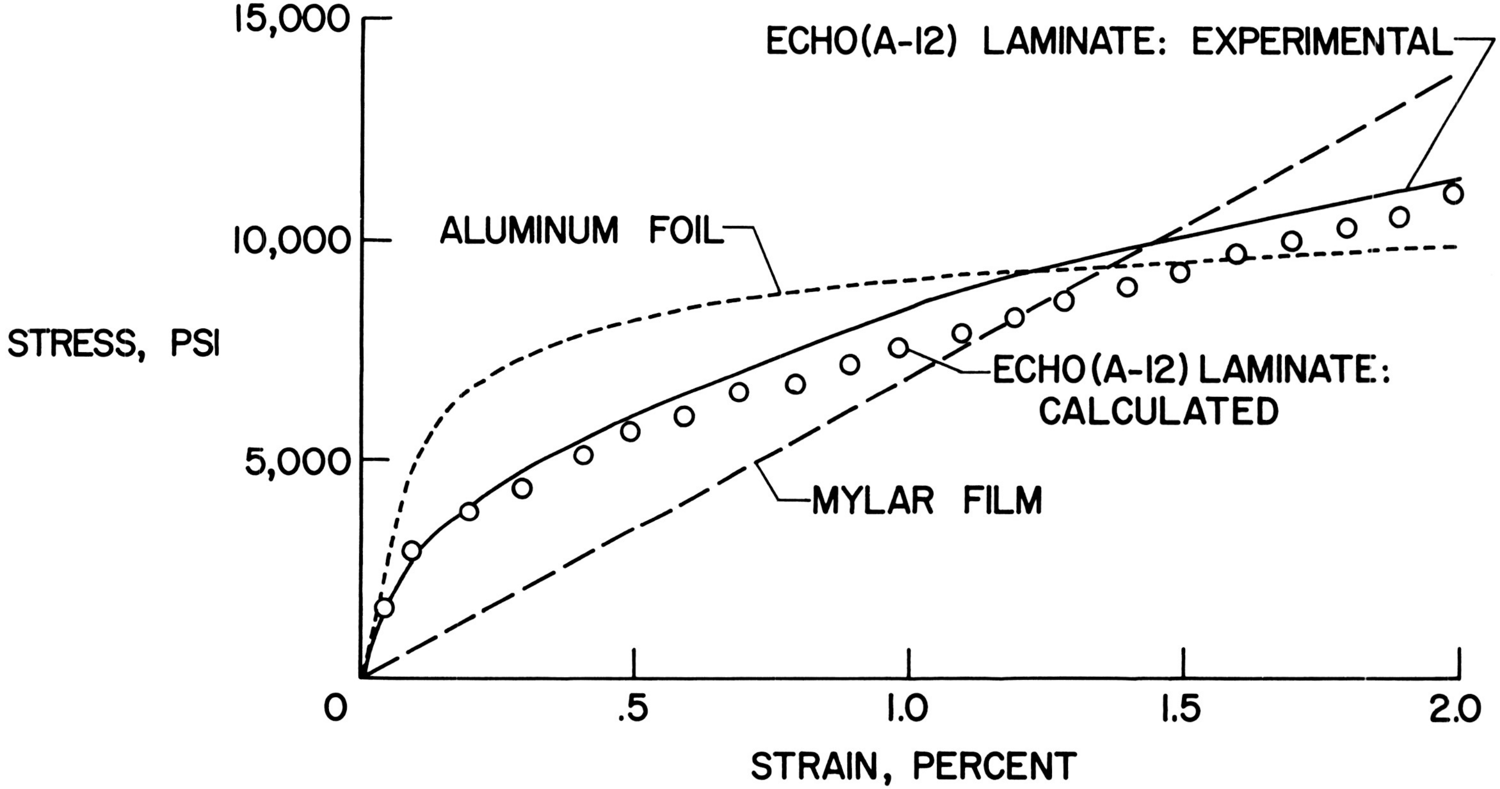

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Figure 3.- Experimental and calculated stress-strain values of Echo (A-12) laminate.

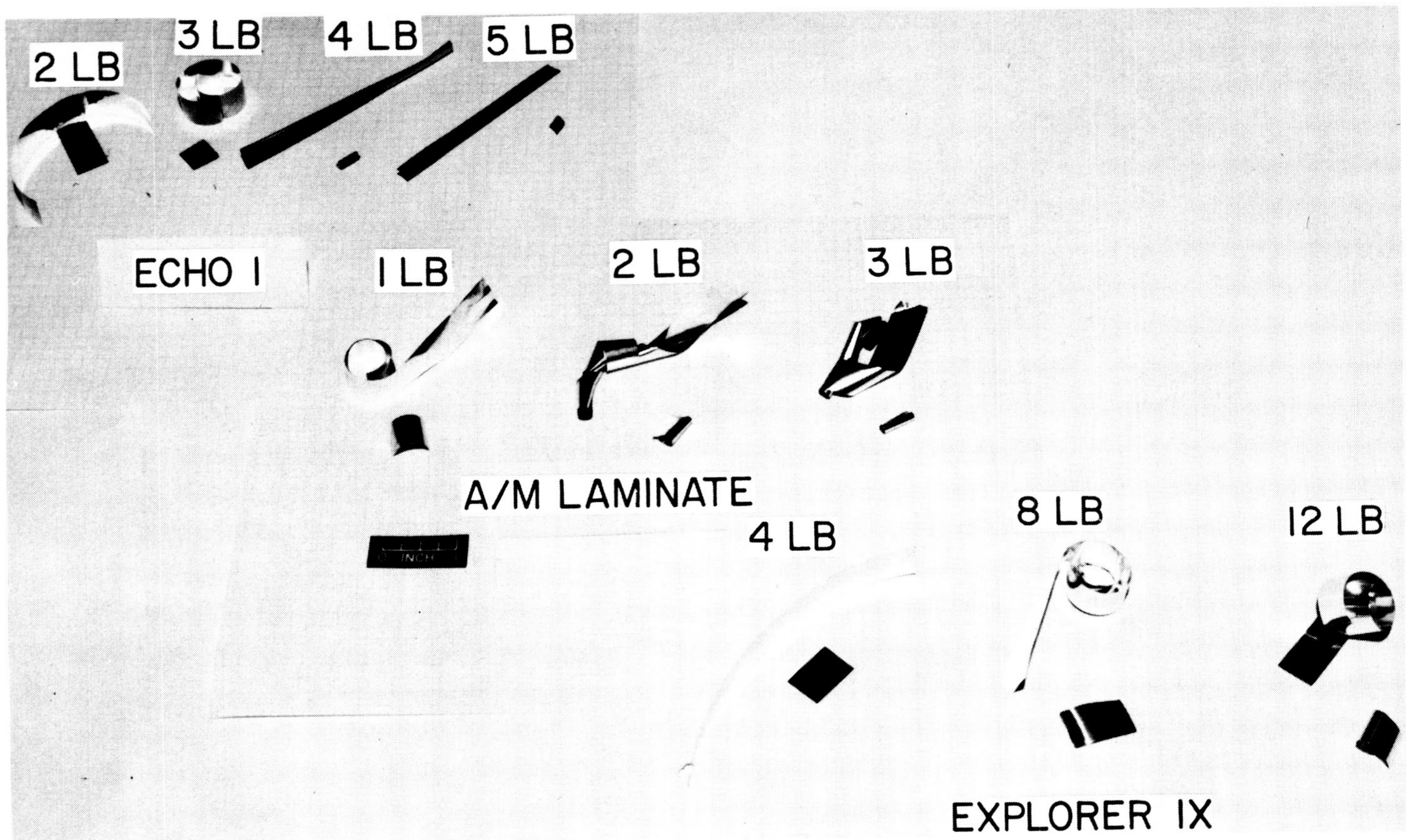

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Figure 4.- Deformed condition of Echo I material, A/M laminate, and Explorer IX laminate after having been subjected to the indicated loads.

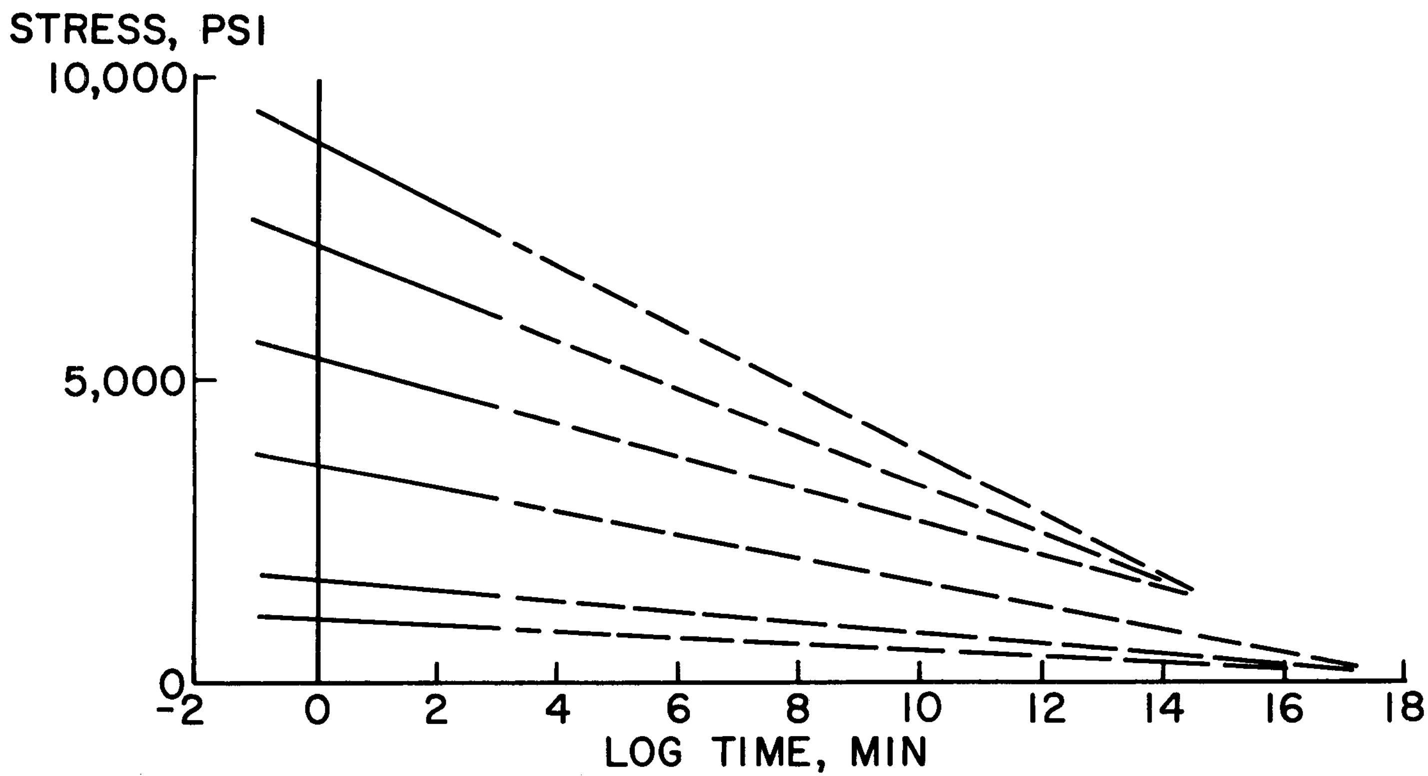

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Figure 5.- Tensile stress relaxation of Echo (A-12) laminate.

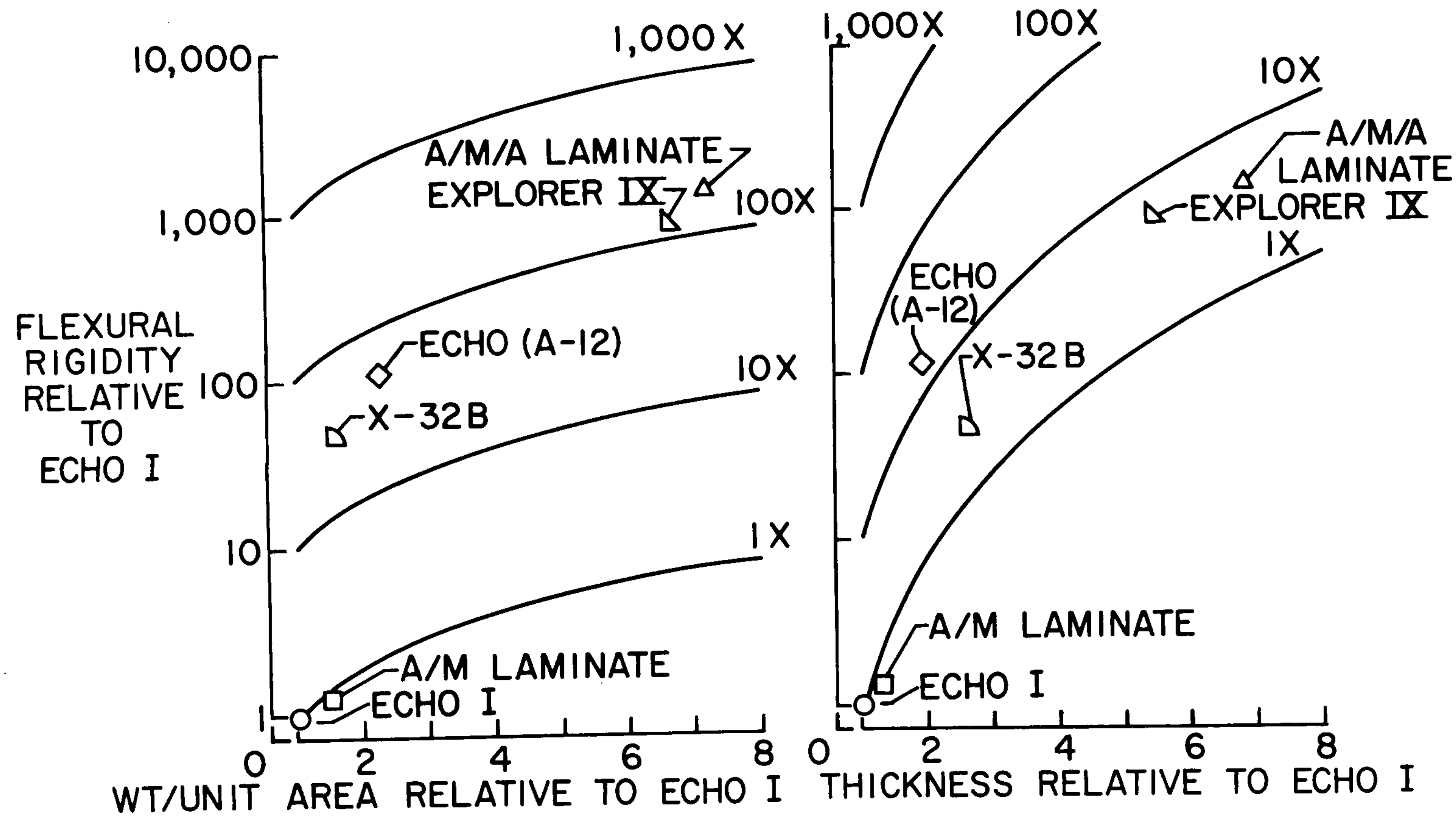

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Figure 6.- Weight and thickness efficiencies of composite materials relative to Echo I material.

NASA-Langley, 1963